Easy Street: An Update on High-Tide Flooding

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WORKING FINAL DRAFT

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Today's Presentation

- Easy Street high-tide flooding
  - Updated my 2019 analysis of Easy Street
  - Data plotted for 1980 to 2021
  - Added references to future water levels using NOAA SLR scenarios
- Searched for similar work or research
  - Obtained access to NASA's Flooding Days Projection Tool
  - Ran setups for Easy Street
- Summary of results (still working)

High-Tide Flooding

- An extreme high tide (absent a storm surge) such that the sea literally spills onto land in some locations, inundating low-lying areas with seawater until the high-tide cycle has passed
- The flooding causes public inconveniences such as standing water in low areas, wet feet, road closures and flooded storm drains (hence being called “nuisance flooding”)
- *Cumulative repercussions* from rising frequencies and durations of floods are beginning to *damage infrastructure and cause other economic and ecosystem impacts*
- HTF frequencies may be represented as count of days in monthly and annual windows for which one hourly sea-level value exceeds the threshold of interest
- A nuisance flooding threshold (water elevation) is best established based on impacts to the local community and/or infrastructure

High-tide Flooding Defined by NOAA

- *High-tide flooding, often referred to as "nuisance" flooding or tidal flooding, is defined by the National Oceanic and Atmospheric Administration (NOAA) as flooding that leads to public inconveniences, such as road closures, overwhelmed storm drains, and deterioration of public infrastructure such as roads*. CRP pg 58
- *NOAA HTF levels are nationally calibrated* (best-fit solution) against NOAA and Emergency Management depth-severity thresholds used in weather forecasting and impact communications to provide a *consistent* coastal-climate resiliency standard
- Across the US, NOAA uses a water levels exceeding about 0.5 meter (1.75 ft.) above high tide as the threshold for High Tide Flooding or "Minor Flooding"
- *NOAA HTF = 1.8 ft. MHHW for Nantucket*
- Thresholds also exist for NOAA Moderate and Major Flooding (2.7 ft. and 4.0 ft. above MHHW, respectively)
- Coastal water levels are referenced to a tidal datum

A Word About Datums

- Tidal Datum (defined by the phase of the tide, i.e. MLW, MSL, MHHW)
  - A standard elevation framework used to track LOCAL water levels as measured by a tidal gauging station
  - Based on the observations during the National Tidal Epoch (19 years) to compute the datum
  - Time it takes the Earth, Moon, and Sun to complete an epoch tidal cycle
  - Considered for revision every ~20-25yrs
  - Averages out long period and seasonal fluctuations
  - Current NTDE is 1983-2001, the next NTDE will be computed on period of 2002-2020
- North American Vertical Datum of 1988 (NAVD 88)
  - Vertical control that spans the entire continent to a single control point
  - The reference system used by surveyors, engineers, and mapping professionals to measure and relate elevations to the Earth's surface
  - Has a fixed reference point as a baseline (i.e., a zero-elevation point), elevation values can be consistently measured and compared among various maps and surveys

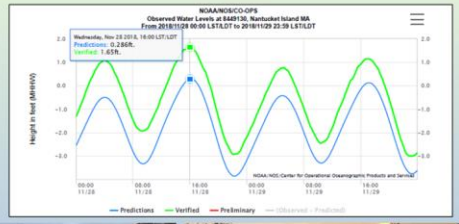
Easy Street High Tide Flooding Impacts

- Easy Street is a *critical route* for goods and services (fuel, food, building materials, persons, equipment etc.) going to the Steamship Authority terminal and lower Broad Street
- Easy Street is major corridor for *trucks, cars, pedestrians, bicycles and tourists*. The sidewalk provides an iconic viewshed of Nantucket Harbor and connects Straight Wharf and Steamship Wharf
- The Easy Street Bulkhead was rebuilt in 2017 to provide additional protection to the sidewalk and roadway. The new timber cap is at elevation 5.0 ft. MHHW and not designed to protect the street from flooding due to storm surge. Original steel cap was at elevation 3.0 ft. MHHW.
- Storm drains at the bulkhead were fitted with backflow prevention valves to minimize flooding during higher water elevations in the harbor (but have challenges)
- Increased amounts of roadway flooding have been observed at some high-tides

How Often is this Occurring? = Tide Gauge + Observed/Documented Road Flooding =

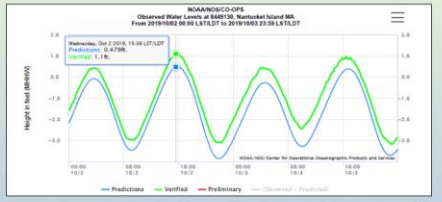
Observation 1

- Photographs were taken Nov. 28, 2018, 4:04 PM.
- The confirmed water level was 1.65 MHHW.
- Depth at Oak St. was estimated to be 6 in.
- Rainfall in the previous 48 hours was a totals 0.6 inches and seems unlikely as a contributor to storm water flooding on the roadway.



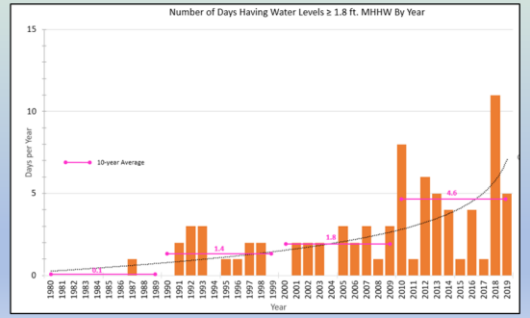
Observation 2

- Photographs were taken on Oct. 2, 2019, 3:55 PM.
- The confirmed water level was 1.1 feet MHHW.
- Depth at Oak St. was estimated to be 1-2 in.
- Rainfall in the previous 72 hours was recorded to be a total of 0.09 inches and is considered insignificant to the flooding observed on the roadway.



1.8 ft. MHHW, How Often Does This Occur?

6 in. or more depth of water

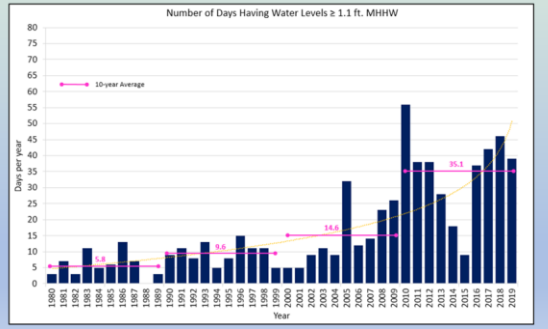


Decade	Average Frequency
1980-1989	Once a decade
1990-1999	1.4 times a year
2000-2009	1.8 times a year
2010-2019	4.6 times a year
2020-2029	?
2040+	Every few days*

* 1.8 feet MHHW is the projected average highest daily high-tide in 2040 using the NOAA Intermediate-High SLR scenario (i.e., on average every other day).

1.1 ft. MHHW, How Often Does This Occur?

1-2 in. or more depth of water



Decade	Average Frequency
1980-1989	5.8 times a year
1990-1999	9.6 times a year
2000-2009	14.6 times a year
2010-2019	35.1 times a year
2020-2029	?
2030+	Every few days*

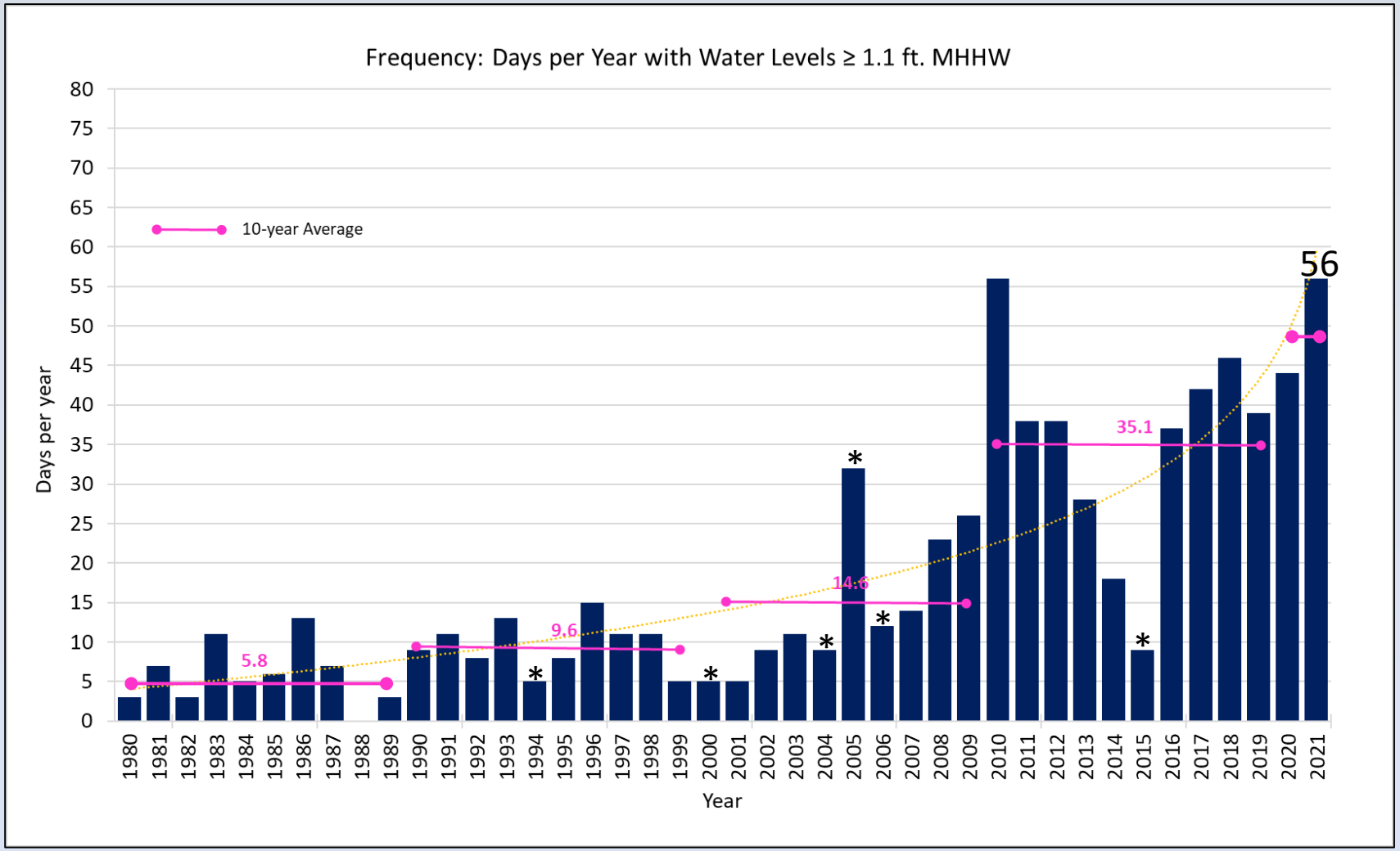
* 1.2 feet MHHW is the projected average highest daily high-tide in 2030 using the NOAA Intermediate-High SLR scenario (i.e., on average every other day).

One Type of Easy Street Nuisance Flooding

- Water covers the road with 1-2 inches of depth at 1.1 ft. MHHW
- Vehicles, bicycles, scooters and/or trucks driving through saltwater
- Unable to use crosswalk at Oak Street
- Water begins to appear on Lower Broad Street
- Potential for vehicle and tire splash/spray

Frequency of 1.1 ft. MHHW

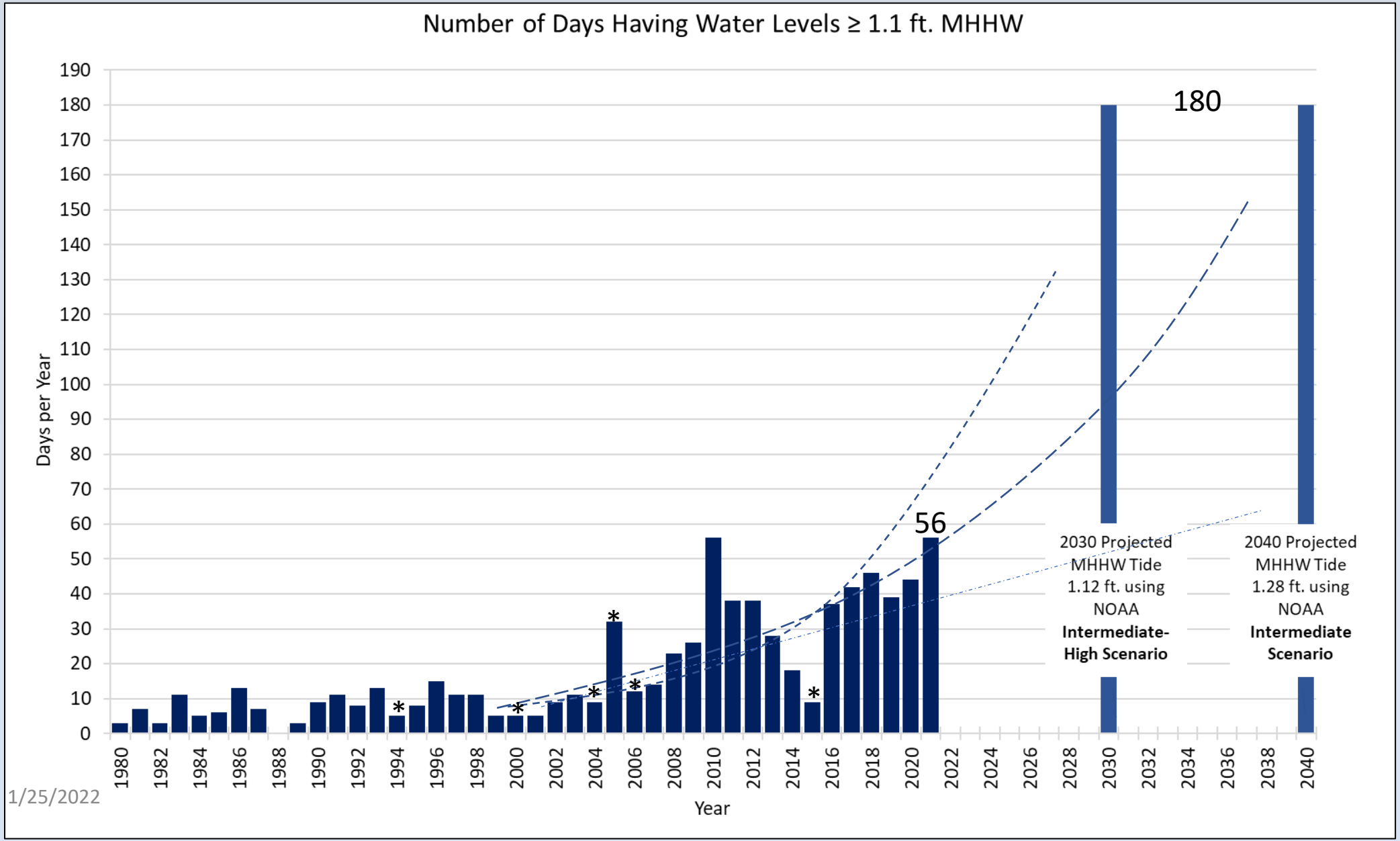
1-2 in. or more depth of water on Easy Street



Decade	Average Frequency
1980-1989	5.8 times a year
1990-1999	9.6 times a year
2000-2009	14.6 times a year
2010-2019	35.1 times a year
2020-2029	TBD
2030+	Every few days

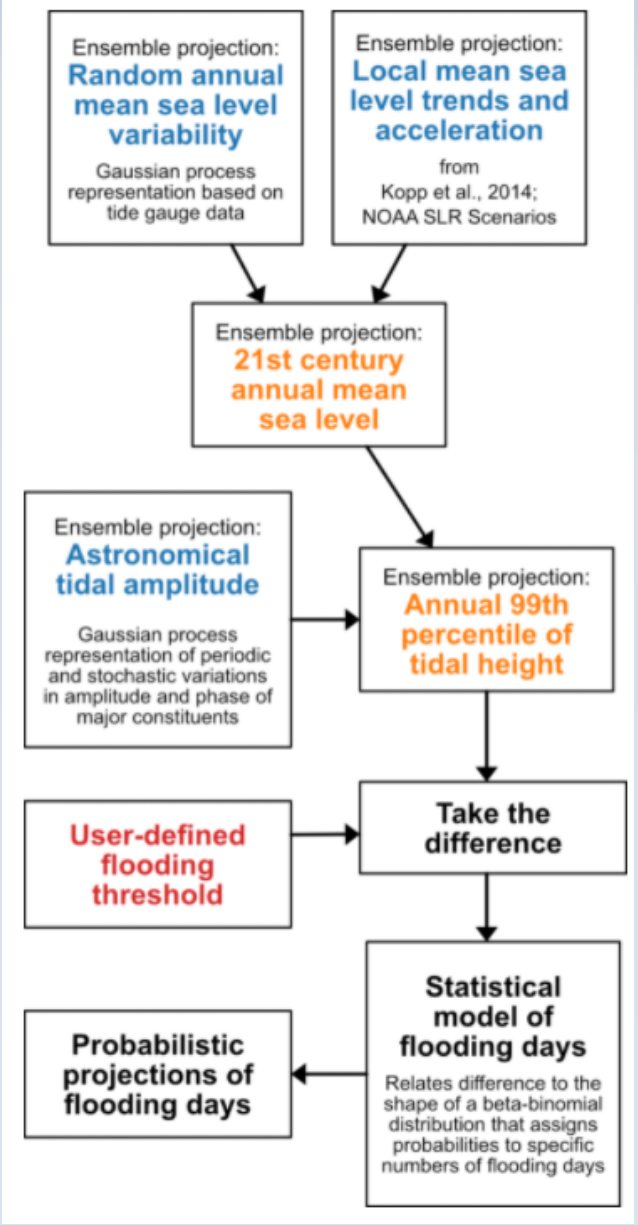
Year	* Data Missing
1994	8.8%
2000	2.1%
2004	10.8%
2005	4.7%
2006	2.7%
2015	4.2%

Easy Street Data Alongside NOAA SLR Scenarios

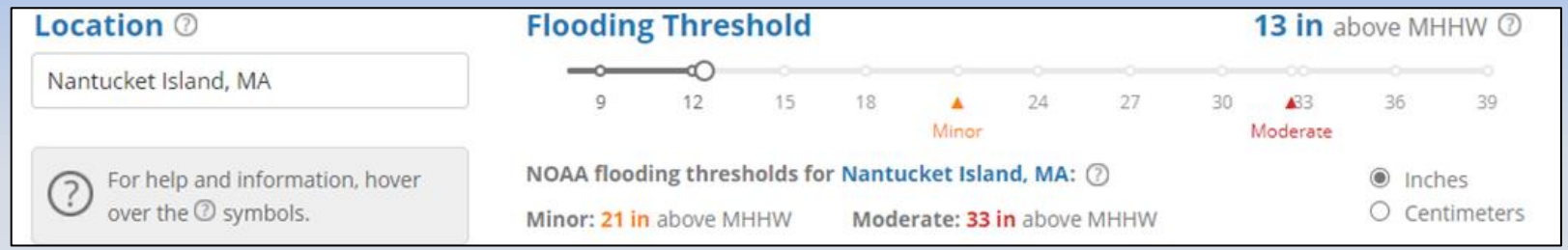


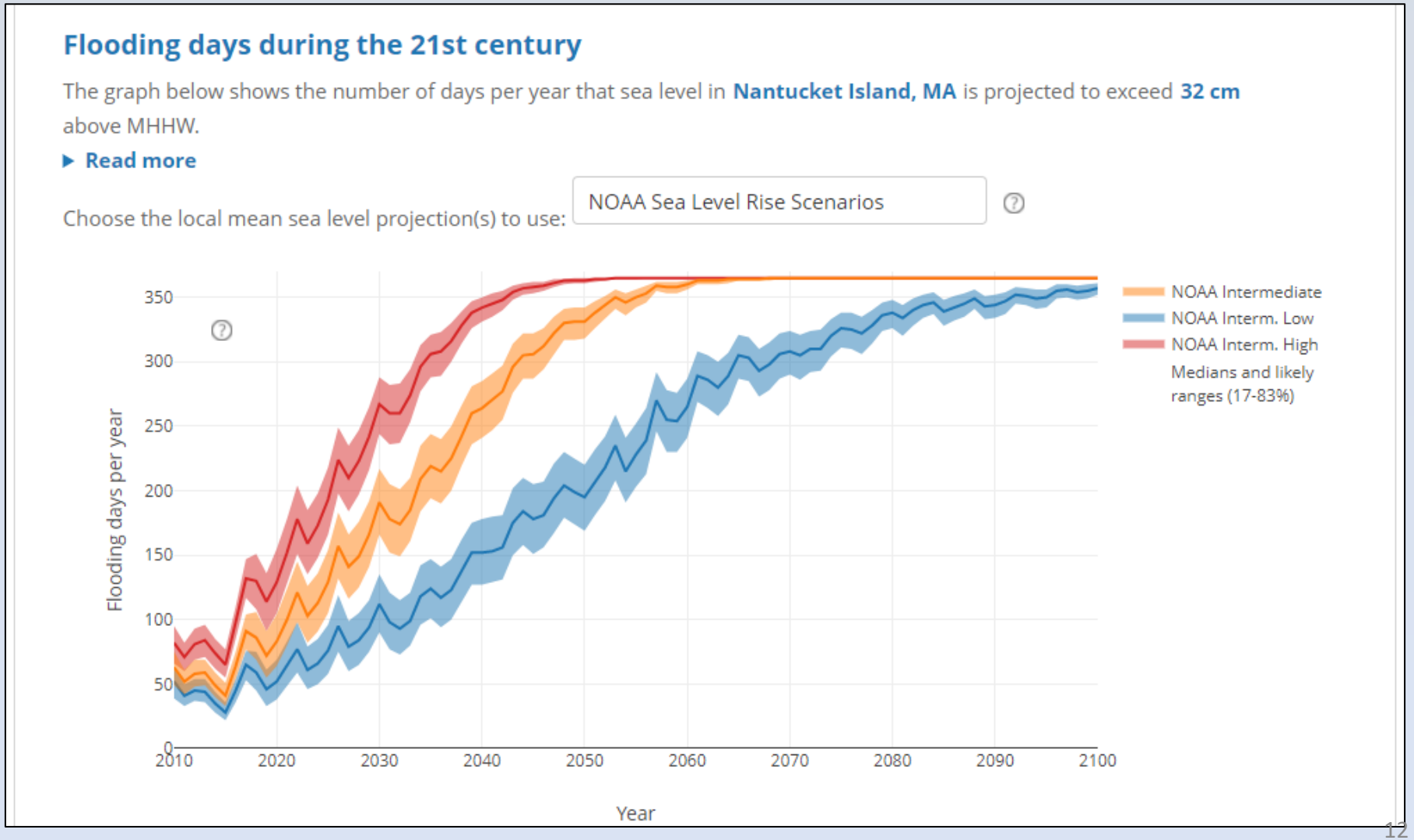
High-tide Specific Modeling

- Model developed by University of Hawaii, NASA, NOAA and others
- Tool for Nantucket available from the NASA Sea Level Change Portal
- Models High-tide Flooding and Sea Level Rise to 2100
- The methodology used to produce the projections in this tool is based on the method of Thompson et al. (2019)
- The method has been applied to more than 90 locations around the U.S. and its territories for which there is sufficient tide gauge data to make robust projections of future flood frequency.
- Includes the ability to select climate scenarios, NOAA flood elevations and evaluate thresholds of interest



Model inputs and outputs for projected tidal flooding on Easy Street at 1.1 ft. MHHW

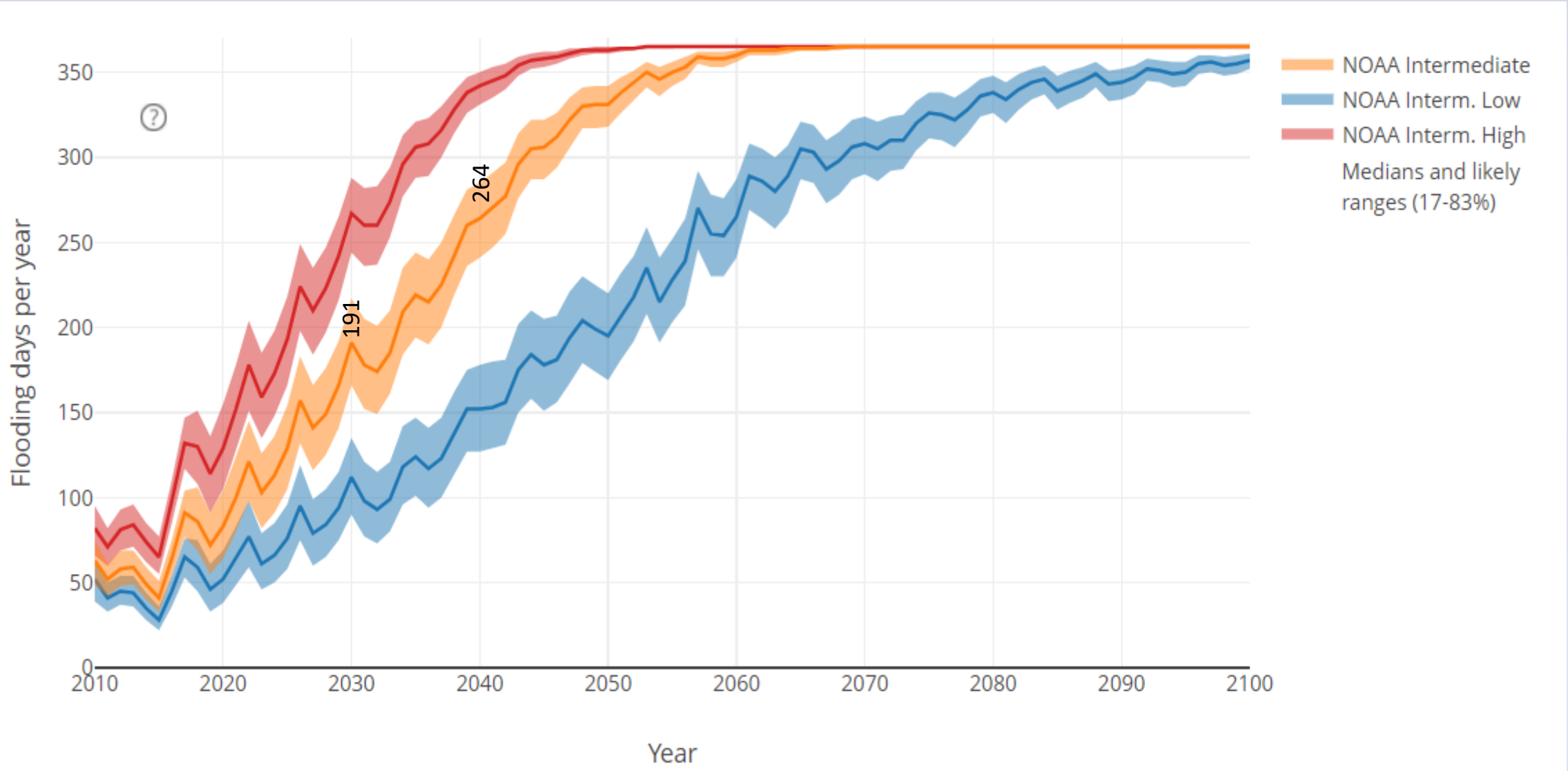




https://sealevel-nexus.jpl.nasa.gov/flood-projection/

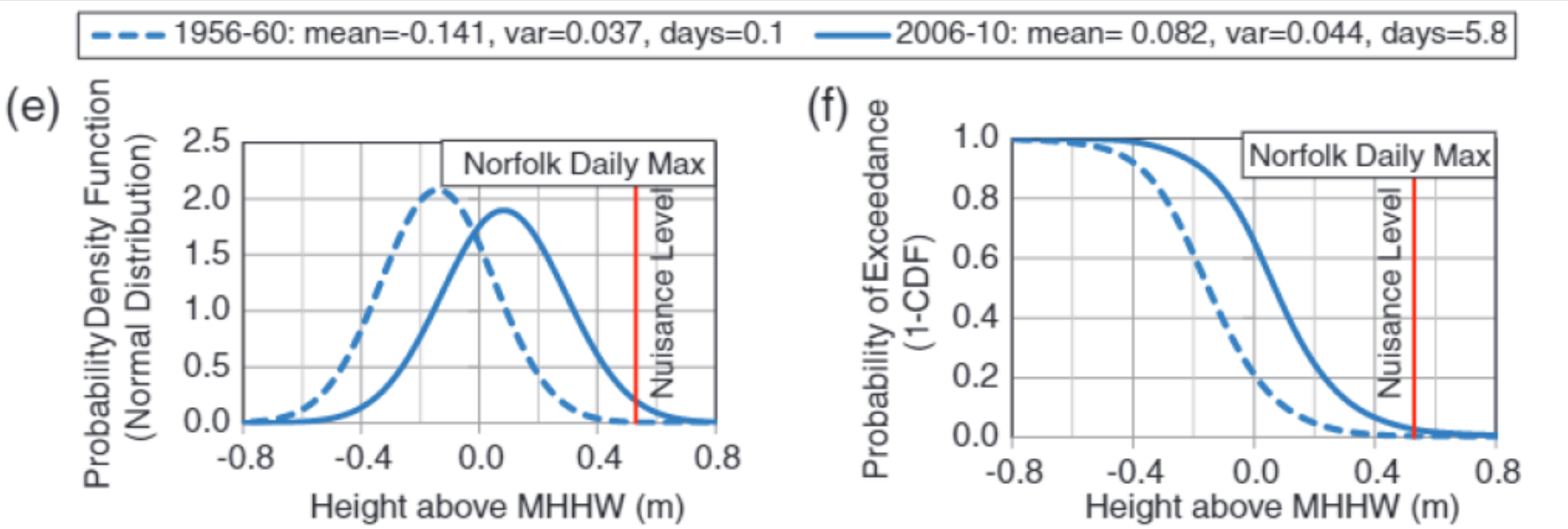
Easy Street High Tide Flooding at 1.1 ft. MHHW

Days per year, on average, 1-2 in. or more depth of water on Easy Street at Oak Street



https://sealevel-nexus.jpl.nasa.gov/flood-projection/

Location Specific Probabilistic Modeling



From: Extreme to the Mean: Acceleration and Tipping Points of Coastal Inundation From Sea Level Rise

Year of Inflection (YOI) for NOAA Flooding Thresholds

YOI is provided as a marker for the potential onset of rapid HTF increases (no. HTF days/year in the decade that follows

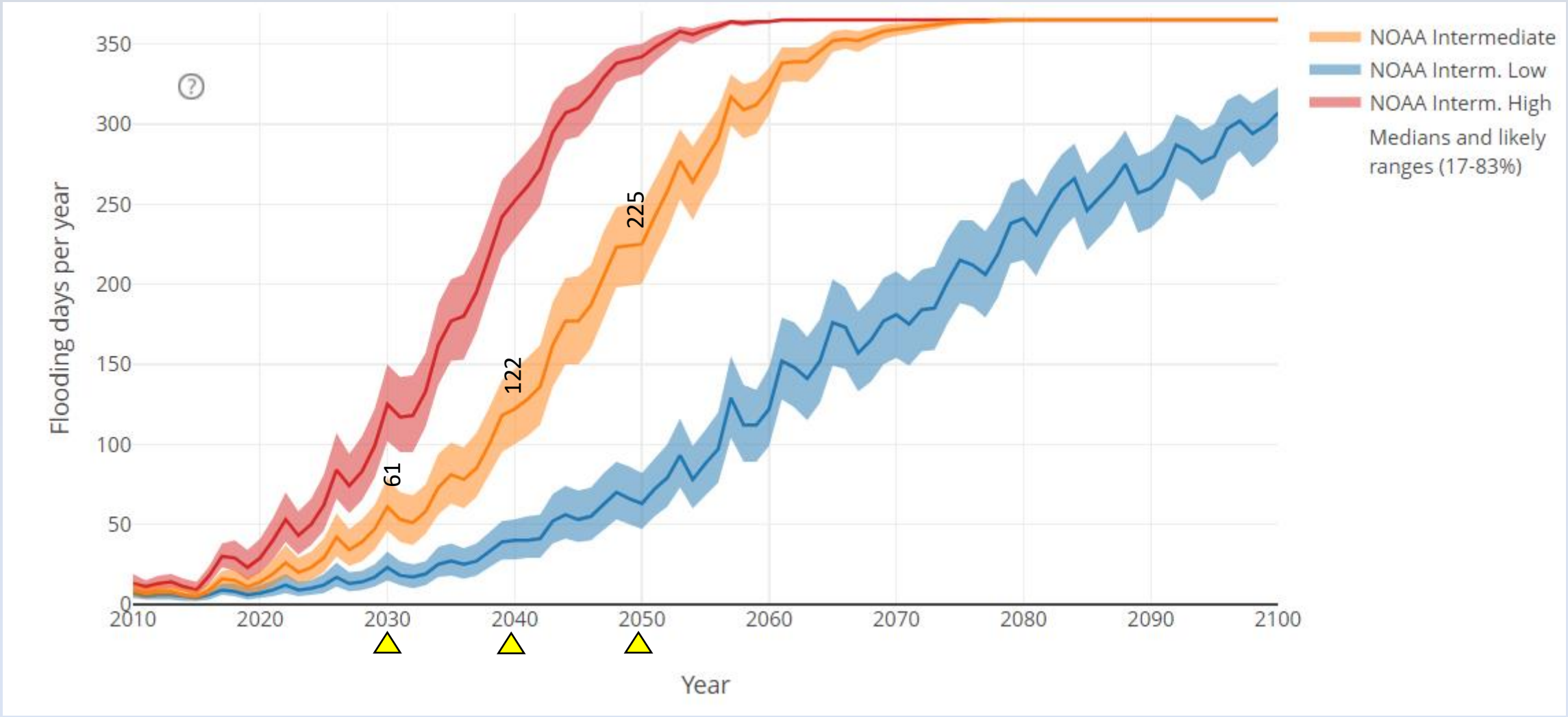
Station Metadata						Intermediate SLR Scenario						Intermediate Low SLR Scenario					
Location				Thresholds (cm)		Minor			Moderate			Minor			Moderate		
	NOAA I	Name	Region	Mino	Moder	YOI	10A	10M	YOI	10A	10M	YOI	10A	10M	YOI	10A	10M
85	8449130	Nantucket Island, MA	Atlantic Coast, North 2	54	83	2033	96	3.4	2051	89	5	2033	26	3.2	2073	20	3.0
86	8447930	Woods Hole, MA	Atlantic Coast, North 2	53	82	2028	57	3.2	2048	49	5.1	2036	26	2.7	2063	9	3.3
87	8443970	Boston, MA	Atlantic Coast, North 2	63	89	2023	46	2.5	2041	46	3.9	2041	39	1.9	2059	22	2.6

NOAA Minor flooding occurs at and above 1.8 ft. (21 in.) MHHW
NOAA Moderate flooding occurs at and above 2.7 ft. (33 in.) MHHW

- The column labelled 10A is the absolute changes in annual counts of HTF days during decades following the YOIs
- The column labelled 10M are relative changes (that is, ten-year multipliers) in annual counts of HTF days during decades following the YOIs.

Rapid increases and extreme months in projections of United States high-tide flooding, Thompson, et. al., (2021) https://www.nature.com/articles/s41558-021-01077-8#Sec16

Easy Street High Tide Flooding at 1.8 ft. MHHW (NOAA Minor Flooding)
(Days per year, on average, 8-10 in. or more depth of water on Easy Street at Oak Street)



https://sealevel-nexus.jpl.nasa.gov/flood-projection/

Recommendations in the Nantucket CRP (2021)

Tidal Flooding

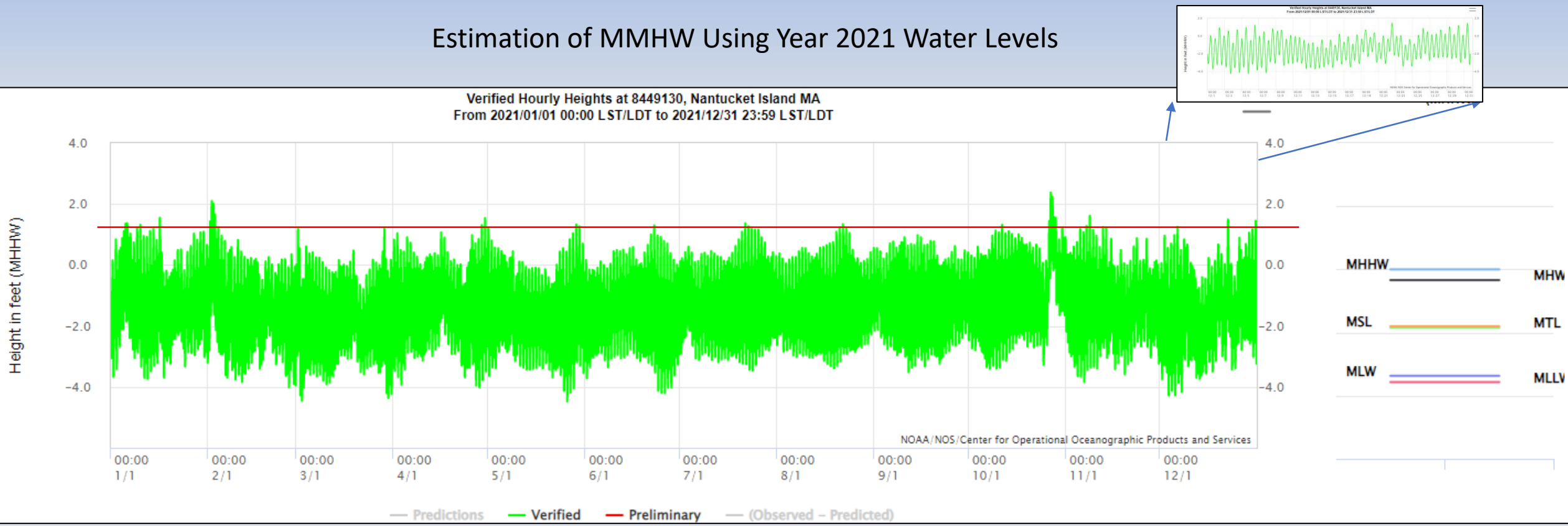
Tidal flooding analysis for the CRP uses mean monthly high water (MMHW) as the tidal level representative of nuisance flooding. Mean monthly high water is the average of the highest monthly tide levels across a defined time period.

The frequency of traditional daily tidal datums (e.g., mean higher high water or mean high water) is too extreme to be considered "nuisance." For example, tidal flooding of a street on a daily basis is not a nuisance, it is a significant disruption to everyday life. By examining mean monthly high water, decision makers are able to understand potential future nuisance issues and address them through mitigation or adaptation actions before the flooding increases in frequency and becomes disruptive. MMHW is typically exceeded 25-35 times a year and is meant to approximate an identified tipping point of 30 flood events per year.

Nuisance Flooding: MMHW & MHHW

MMHW	MHHW
Monthly Mean High Water	**Mean Higher High Water**
Represents monthly "flooding events"	Represents daily "flooding events"
Is typically exceeded 25-35 times a year and is meant to approximate an identified tipping point of 30 flood events per year (Nantucket CRP 2021)	Is exceeded hundreds of times per year
MMHW is the average of the highest monthly tide levels across a defined time period (Nantucket CRP 2021)	MHHW is a site-specific datum determined by averaging the highest of the two high tides that occur each day over a 19-year tidal epoch (USGS, 2018)
MMHW results can change if *time period changes*, unlike MHHW which is fixed on a 19-year tidal epoch	MHHW is a standard tidal datum used by NOAA MMHW is not a standard datum used by NOAA
Suggested as a threshold indicator for when sea level rise will first affect neighborhood habitability and require adaptation, protection and/or retreat	
The number of 30 tidal floods per year was recently hypothesized as being a possible tipping point for livability (Sweet and Park, 2014)	

Estimation of MMHW Using Year 2021 Water Levels



Date	Time	MHW	Datum
1/16/2021	14:24	1.5	MHHW
2/2/2021	2:48	2.11	MHHW
3/1/2021	13:42	1.24	MHHW
4/30/2021	3:00	1.56	MHHW
5/29/2021	3:00	1.33	MHHW
6/22/2021	23:06	1.28	MHHW
7/21/2021	22:24	1.4	MHHW
8/22/2021	0:18	1.32	MHHW
9/14/2021	19:06	0.95	MHHW
10/27/2021	4:00	2.38	MHHW
11/8/2021	14:30	1.66	MHHW
12/31/2021	9:18	1.45	MHHW

Avg.	1.515	MHHW
Max.	2.38	MHHW
Min.	0.95	MHHW

Observations

The Mean Monthly High Water (MMHW) for 2021 is 1.5 ft. MHHW (the NOAA Minor Flooding Threshold is 1.8 ft. MHHW)

MMHW does appear to be ~25-35 times a year based on graph above

Elevations below MMHW flood more frequently!

https://tidesandcurrents.noaa.gov/waterlevels.html?id=8449130&units=standard&bdate=20210101&edate=20211231&timezone=LST/LDT&datum=MHHW&interval=h&action=

Flooding Frequency – An Important Point

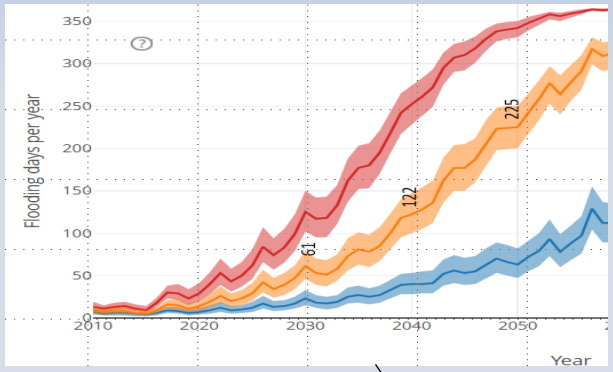
- Tidal flooding events needs to consider impacts
  - Where infrastructure sits and how it is affected
  - Impact to the community and businesses
- The number of 30 tidal floods per year was hypothesized as being a possible tipping point for livability (Sweet and Park, 2014)
  - Adopted by NYC and others
  - Recommended in the Nantucket CRP
- Within Norfolk, VA, Charleston, SC, and Miami Beach, FL, large-scale engineering solutions are being planned or implemented when only about 5-10 days of flooding per year are being experienced
- Needs careful consideration if used to trigger action

Closing Thoughts (page 1 of 2)

- Easy Street is a critical transportation and pedestrian route
- Nantucket tide gauge data was downloaded and analyzed from 1980 thru 2021
  - The frequency of Easy Street Nuisance Flooding is increasing
  - Easy Street Nuisance Flooding with a depth of at least 1-2 in. of water/saltwater (1.1 ft. MHHW) occurred 56 times in 2021
- NOAA SLR scenarios (Intermediate-High and Intermediate) tools indicate Easy Street Nuisance Flooding may occur every other day, on average, starting in 2030-2040
- The NASA Flooding Days Projection Tool is available for analysis of Easy Street Nuisance Flooding
  - Scenarios were developed and analyzed for Nantucket using the NASA tool
  - The NASA tool results agree with the analysis of tide gauge data
  - The NASA tool may be applied to other locations of particular interest (Washington Street, Easton Street, South Beach Street, etc.)
- *Changes in HTF frequency will not be incremental in the coming decades* but will include inflections in the rate of increase
  - HTF events cluster by months and years
- *Inflections are specific to a tide gauge location, SLR scenario and flooding threshold*
  - Easy Street Nuisance Flooding (1-2 in. of water) appears to be at point of inflection

Closing Thoughts (page 2 of 2)

- NOAA Nuisance Flooding (same as NOAA Minor Flooding) on Nantucket occurs when coastal water levels reach 1.8 ft. MHHW.
  - This level was established with an approach for reporting consistency across the US, understanding that it might not apply to specific areas
  - *In 2040, Easy Street Flooding at 1.8 ft. MHHW or higher is estimated to occur, on average, more than 100 times a year*
  - *YOI is 2033 for the NOAA Minor Flooding (≥1.8 ft MHHW), using the Intermediate and Intermediate-low SLR scenarios*
  - NOAA Minor Flooding on Easy Street produces a water depth of approximately 10 in. at the intersection with Oak Street
- The Nantucket CRP (2021) suggests that nuisance flooding that occurs typically 25 to 35 times per year is a tipping point of interest
  - Easy Street Nuisance Flooding of 25-35 times/year was first recorded in 2005 and more consistently seen starting in 2010
  - The Nantucket CRP uses MMHW (Mean Monthly High Water) as the tidal representative of nuisance flooding (occurs typically 25 to 35 times per year)
    - Side note: may be easily with MHHW (Mean Higher High Water) when communicating with the public
- Some jurisdictions apply a frequency threshold of 5 to 10 nuisance flooding days per year (add'l time for planning, permitting, design, construction, etc.)



~100 times a year in 2040
NOAA Intermediate Scenario

2 times a year in 2021
(Max. no. 11 in 2018)

MMHW (Approx)
25-35 times a year (2021)

Elev. 1.1 ft
50+ times a year (2021)

Easy Street @ Oak Street

Elev. 0.9 ft CB rim

Storm Drain

Top Easy Street Bulkhead Elev. 5.0

5.0
NOAA Major
Elev. 4.0 ft
NOAA Moderate
3.0
Elev. 2.7 ft
NOAA Minor
2.0
Elev. 1.8 ft
Elev. 1.1 ft
1.0
1-2 in. deep on Easy St
0 Ft. MHHW
MSL